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ON THE THERMAL DURABILITY OF SOLAR PROMINENCES, OR HOW TO EVAPORATE A PROMINENCE ?

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ABSTRACT

We investigate the thermal disappearance of solar prominences under strong perturbations due to wave heating, Ohmic heating, viscous heating or conduction. Specifically, we calculate how large a thermal perturbation is needed to destroy a stable thermal equilibrium, and find that the prominence plasma appears to be thermally very rugged. Its cold equilibrium may most likely be destroyed by either strong magnetic heating or conduction in a range of parameters which is relevant to flares.

I. INTRODUCTION

The thermal equilibrium of a prominence may be modeled using the approximate equation:

$$h\rho - \rho^2 Q(T) + j^2/\sigma + \eta\, v^2/\ell^2 + k_o\, T_c^{7/2}/L^2 = 0$$

where

$h\rho^2$	is the magnetic heating, assumed constant per unit of mass.
j^2/σ	is the Ohmic heating. We will assume $\sigma = \sigma_o\ T^{3/2}$ with σ_o being a constant.
$\eta v^2/\ell^2$	is the viscous heating with $\eta = \eta_o T^{5/2}$, η_o being a constant.
$k_o T_c^{7/2}/L^2$	is the thermal conduction with T_c the coronal temperature and k_o a constant.
$\rho^2 Q(T)$	is the radiative cooling.

The quantities ρ, T, v, j have their usual meaning. Here L corresponds to the thermal length-scale along a magnetic field line from the photosphere to the prominence, and ℓ corresponds to the prominence thickness. $Q(T)$ is the piecewise cooling function given by Hildner (1974) in the form $Q(T) = \chi T^\alpha$ with:

Temperature (K)	χ (MKSA)	α
$T < 1.5 \times 10^4$	1.759×10^{-13}	7.4
$1.5 \times 10^4 < T < 8 \times 10^4$	4.290×10^{10}	1.8
$8 \times 10^4 < T < 3 \times 10^5$	2.860×10^{19}	0
$3 \times 10^5 < T < 8 \times 10^5$	1.409×10^{35}	-2.5
$T > 8 \times 10^5$	1.970×10^{24}	-1.0

We now consider separately the balance between radiative losses and magnetic heating, Ohmic heating, viscous heating, or conduction.

II. WAVE HEATING VS. RADIATION

This equilibrium is described by the following set of equations:

$$h_p\rho_p = \rho_p^2\, Q(T_p) \text{ in the prominence (subscript p)}$$

$$h_c\rho_c = \rho_c^2\, Q(T_c) \text{ in the corona (subscript c).}$$

Hence $$Q(T_p)/Q(T_c) = \rho_c/\rho_p, \text{ if } h_p = h_c.$$

With $T_c = 10^6$K and a ratio $\rho_p/\rho_c = 100$, we get a reasonable temperature of T_p = 8425 K for the prominence. Now for heating at constant gas pressure, this equilibrium is:

$$[Q(T)/Q(T_c)]\ (T_c/T) = h/h_c.$$

Thus, new equilibrium temperatures are given by $Q(T)/T$ = constant x h. For a given heating rate there are generally two solutions, a cold one and a hot one. The cold one does not exist anymore above T_m = 8×10^4 K, due to the behavior of Q(T), and the prominence disappears when

$$h > h_m = h_c Q(T_m) T_c/[Q(T_c)\ T_m].$$

With $T_m = 8 \times 10^4$K, we get $h_m/h_c = 213.7$. Hence, a strong magnetic heating is necessary to evaporate a prominence. Such a heating could be produced by enhancement of the ambient coronal heating mechanism or by magnetic energy released during a flare.

III. JOULE HEATING VS. RADIATION

This balance results from the following equation:

$$j^2/\sigma = \rho^2 Q(T), \qquad \text{with } \sigma = \sigma_o\ T^{3/2}.$$

The current density j can be expressed in terms of the transverse magnetic field $B_\perp$ by using the mechanical equilibrium condition:

$$\rho g = jB_\perp .$$

where g is the solar gravity. The equilibrium temperature is then given

$$T_p = [g^2/(B_\perp^2 \chi\sigma_o)]^{(1/\alpha + 3/2)} .$$

With a transverse magnetic field $B_\perp$ of 7G (Leroy et al. 1983), and a classical conductivity of $\sigma_o = 8 \times 10^{-4}$ MKSA, we get an unusually low value of $T_p = 1092$ K. In order to obtain a realistic prominence temperature we need to increase the resistivity by a factor of 10^6, and then we obtain a more reasonable temperature of 5157 K. Disrupting a prominence by current dissipation requires an even larger anomalous resistivity. With the same analysis as above, it is necessary to increase the anomalous resistivity yet further by a factor of 5×10^5 or 5×10^{11} altogether. Alternatively, one could also decrease the magnetic field by a factor of 700.

IV. VISCOUS HEATING VS. RADIATION

This equilibrium may be described by the following equation:

$$\eta v^2/\rho^2 = p^2\, Q(T) \qquad \text{with } \eta = \eta_o T^{5/2}.$$

Let us compare viscous and Ohmic heating. The viscous and magnetic Reynolds numbers R_e and R_m are given by:

$$R_e = v\ell\rho/\eta, \qquad\qquad R_m = v\ell\, \mu_o\sigma,$$

In prominence conditions ($T = 8000$ K, $\rho = 10^{-12}$ g cm^{-3}, $\ell = 3000$ km, and $v = 2$ km s^{-1}, Schmieder et al. 1984), we obtain with classical coefficients σ_o and η_o:

$$R_m \sim 4 \times 10^6 \text{ and } R_v \sim 10^8.$$

Therefore, viscous dissipation is smaller than ohmic heating. Note that this is not true in the corona (Hollweg 1985). The equilibrium temperature is given by

$$T_p = [(\eta_o v^2)/(L^2\rho^2\chi)]^{1/(\alpha-5/2)} = 870 \text{ K}.$$

In order to get a realistic prominence temperature on the order of 5700 K, we need to increase the viscous resistivity by a factor of at least 10^4. Perturbing the equilibrium at constant gas pressure (ρT = constant), and constant mass flux (ρv = constant), we obtain the expression

$$Q(T)/T^{13/2} = \text{constant} \times \eta_o .$$

for the new temperature. A cold solution does not exist above $T_m = 1.5 \times 10^4$ K due to the behavior of Q(T). Consequently, the prominence disappears when

$$\eta_o > \eta_{om} = \eta_{op}\, [Q(T_m)/Q(T_p)]\, (T_p/T_m)^{3/2} .$$

With $T_p = 5700$ K we obtain an extra anomalous factor $\eta_{om}/\eta_{op} = 2.4$. This means that anomalous viscosity is a possible candidate to evaporate a prominence.

V. CONDUCTION VS. RADIATION

When conduction balances radiation, we have the following equilibrium:

$$\rho^2 Q\ (T) = k_o\ T_c^{7/2}/L^2, \qquad (k_o = \text{constant}).$$

L is the thermal length-scale along magnetic lines coming from the photosphere to the prominence. With $\rho = 10^{-12}$ g cm^{-1} and $T_c = 10^6$ K, this equation provides T_p = 3556 K with L = 3 x 10^4 km, or T_p = 4786 K with L = 10^4 km or T_p = 8917 K with L = 10^3 km, so conduction is important in the energy budget of prominences. Now if we perturb this equilibrium at constant gas pressure and constant L, we obtain

$$Q(T)/T^2 = \text{constant} \times T_c^{7/2}.$$

A cold solution does not exist above $T_m = 1.5 \times 10^4$ K, and so the prominence disappears when

$$T_c > T_{cm} = T_c\ [Q(T_m)/Q(T_p)]^{2/7} (T_p/T_m)^{4/7} = T_c\ (T_m/T_p)^{2(\alpha-2)/7}\ .$$

With L = 3 x 10^4 km, we get T_{cm}/T_c = 9.21. Hence, the appearance of a hot region in the neighborhood of a prominence is a possible mechanism to heat and evaporate a prominence. Such a hot temperature region could be the consequence of a flare.

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